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Sensitivity of northern hemisphere air temperatures and snow expansion to North Pacific sea surface temperatures in the Goddard Institute for Space Studies general circulation model

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Abstract. Circum-Pacific marine and terrestrial records indicate a series of temperature-inferred oscillations during the late glacial. While many previous studies have probed the role of the North Atlantic in these oscillations, we test the sensitivity of the northern hemisphere air temperatures to North Pacific sea surface temperature (SST) oscillation in the Goddard Institute for Space Studies general circulation model. The effect of a colder North Pacific is to cool air temperatures over North America, as well as parts of Europe and Asia. The colder SSTs result in a large hemispheric response due to the loss of water vapor as a greenhouse gas. The large sensitivity of the northern hemisphere to a North Pacific SST change has implications for the ice age climate as well as the late glacial interval. The results of this experiment provide a rapid mechanism for widespread cooling which has not been previously addressed.

1. Introduction

Rapid climate instability as demonstrated in the Greenland ice cores [*Dansgaard et al.*, 1989; *Taylor et al.*, 1993] presents an intriguing question concerning its origin. While we know that the North Atlantic Ocean was undergoing similar dramatic changes in ocean temperature and ice-rafted debris intervals [*Bond et al.*, 1992], until recently it has not been clear whether the North Pacific region also experienced these changes and how the rapid shifts relate to changes in terrestrial midlatitude records. Several detailed accelerator mass spectrometry (AMS) carbon 14 stratigraphic studies in the last 2 years demonstrate that the North Pacific did experience rapid climate variability during the late Pleistocene, both on land [*Peteet and Mann*, 1994] and in the ocean [*Kötilainen and Shackleton*, 1995; *Thunell and Mortyn*, 1995; *Kennett et al.*, 1995]. While the origin of colder North Pacific SSTs remains as yet a mystery, we explore the question of what effects a colder North Pacific would have had on the terrestrial environment using the Goddard Institute for Space Studies (GISS) general circulation model (GCM), along with a related question concerning the relationship of the changing sea surface temperature (SST) in both ocean basins to temperate glacial growth.

One of the optimal time intervals to study the relationship between marine, terrestrial, and ice core data with high temporal resolution is the late glacial climate that followed the last ice age. Well defined in ice cores, it is also clearly recognized in marine and terrestrial records surrounding the North Atlantic and, recently, also from the North Pacific. We thus use the late glacial paleorecord and the GISS GCM to test hypotheses concerning the atmospheric response to a colder North Pacific and the degree to which it influences snow cover.

2. Background

High latitudes are particularly responsive to forcing because of sea ice and albedo feedbacks. While some authors predict that greenhouse warming, including warmer oceans at high latitudes, will result in rapid meltback in alpine glaciers [*Oerlemans and Fortuin*, 1992], others claim from paleoclimatic data that the ice cover at high latitudes will actually increase [*Miller and deVernal*, 1992]. This is an important question in estimates of future climate warming, as well as for understanding the climate system. From past accumulation rates measured in polar ice cores, glacial intervals are characterized by half the snowfall that was characteristic of the Holocene [*Alley et al.*, 1993]. However, the question of the response of present polar glaciers to recent climate warming is controversial. Satellite altimeter measurements [*Zwally et al.*, 1989] and mass budget analyses [*Bentley and Giovinetto*, 1991] over Greenland suggest recent polar ice sheet growth, but *Jacobs* [1992] argues that these reports must be interpreted with caution because the data are of limited temporal duration and are often of high spatial variability. For example, it is certainly possible that the Antarctic ice sheet has grown as sea level has risen over the past century, but the opposite conclusion is equally tenable.

While a wealth of paleoceanographic data exists on temperature changes in the North Atlantic and their relationship to short-term events such as the Younger Dryas cooling [*Broecker et al.*, 1985; *Lehman and Keigwin*, 1992; *Duplessy et al.*, 1992], much fewer data exist for the North Pacific, and hence it has been the focus of much less attention in climate modeling. However, in the last decade a focus on high-resolution marine [*Keigwin*, 1987; *Kallel et al.*, 1988; *Keigwin and Jones*, 1990; *Boltovskoy*, 1990; *Linsley and Thunell*, 1990; *Zahn et al.*, 1991; *Keigwin and Gorbarenko*, 1992; *Keigwin et al.*, 1992; *McDonald*

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Table 1. Sites Located in Figure 1 Showing North Pacific Late Glacial Oscillations in Isotopes, Ice-Rafted Debris, or Fauna (Marine) and Palynology and/or Macrofossils (Terrestrial) Suggesting Changes in Ocean Circulation and/or Paleoclimate

Symbol	Core	Location	Reference
		Marine Sites	
A	123	1°S, 164°E	*Boltovskoy* [1990]
B	769	9°N, 121°E	*Linsley and Thunell* [1990]
C	CH84-14	41°N, 142°E	*Kallel et al.* [1988]
D	RAMA 44	53°N, 164°E	*Keigwin* [1987], *Keigwin et al.* [1992]
E	882	50°N, 167°E	*Kotilainen and Shackleton* [1995]
F	883	51°N, 168°E	*Kotilainen and Shackleton* [1995]
G	GC-36	50°N, 168°E	*Gorbarenko* [1996]
H	GC-11	53°N, 179°E	*Gorbarenko* [1996]
I	PAR 87-A	54°N, 149°W	*Zahn et al.* [1991]
J	station P	50°N, 145°W	*Zahn et al.* [1991]
K	AHF 28181	33°N, 119°W	*Thunell and Mortyn* [1995]
L	AHF 11343	33°N, 120°W	*Thunell and Mortyn* [1995]
M	480	28°N, 112°W	*Keigwin and Jones* [1990]
		Terrestrial Sites	
1	Japan	36°N, 138°E	*Tsukada* [1967], *Fuji* [1982]
2	Japan	43°N, 142°E	*Igarashi et al.* [1993]
3	Kodiak Island	57°N, 154°W	*Peteet and Mann* [1994]
4	SE Alaska	58°N, 137°W	*Engstrom et al.* [1990]
5	British Columbia	54°N, 132°W	*Mathewes* [1993]
		51°N, 128°W	*Hebda* [1983]
6	British Columbia	49°N, 123°W	*Mathewes* [1973]
7	Washington	48°N, 125°W	*Heusser* [1973]

and Pederson, 1995; *Kennett et al.*, 1995; *Gorbarenko*, 1996] sediments suggests that North Pacific circulation and climate may have changed during the Younger Dryas. Terrestrial pollen and glacial evidence [*Tsukada*, 1967; *Fuji*, 1982; *Hebda*, 1983; *Engstrom et al.*, 1990; *Igarashi et al.*, 1993; *Mathewes*, 1993; *Peteet and Mann*, 1994; *Reasoner et al.*, 1994] from the North Pacific (Table 1, Figure 1) showing late glacial change indicates that the North Pacific region experienced several oscillations in temperature during the transition from full glacial to Holocene conditions.

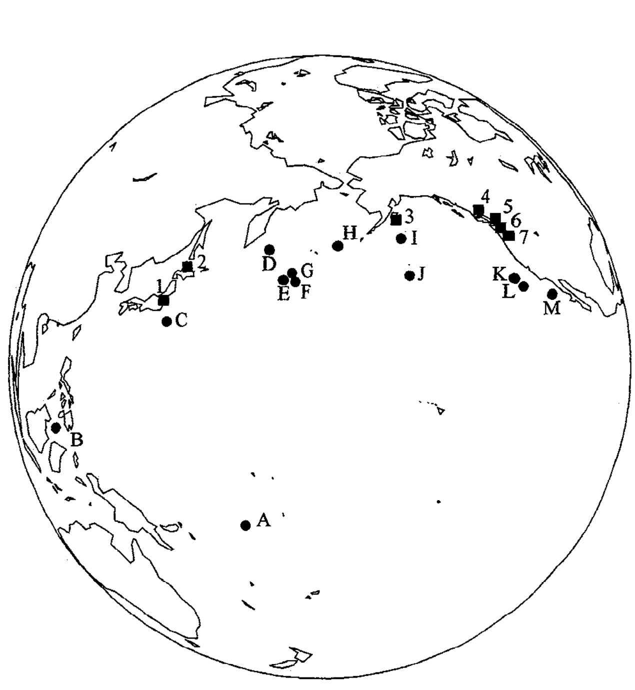

Figure 1. Sites recording late glacial oscillations from marine (circles) and terrestrial cores (squares). References are listed in Table 1.

2.1. Younger Dryas Climate Interval: Evidence for a Colder North Atlantic Region

A unique opportunity to examine the relationship between ice growth and sea surface temperature is provided by the Younger Dryas cooling, a late Pleistocene climatic oscillation that occurred approximately 11,000–10,000 ^{14}C years B.P. North Atlantic SSTs were considerably cooler during this time, and the North Atlantic polar front re-advanced almost to its glacial position [*Ruddiman and McIntyre*, 1981]. While the Greenland Ice Sheet Project 2 (GISP2) ice core at 72.6°N shows a drop in annual layer thickness by a factor of 2 during the Younger Dryas [*Alley et al.*, 1993], European glacial records in regions adjacent to the North Atlantic indicate Younger Dryas re-advances, suggesting that the feedback at middle to high latitudes is a rapid positive one. Scandinavian moraines are quite conspicuous, with the largest and most dominant end moraines along the entire coast of Norway [*Anderson*, 1979; *Larson et al.*, 1984]. In Scotland alone, glaciers actually reformed from a completely deglaciated surface [*Sissons and Sutherland*, 1976; *Gray and Lowe*, 1977].

A growing body of research in the last decade has indicated that the Younger Dryas was not restricted to the European side of the Atlantic [*Peteet*, 1995]. In addition to the Greenland ice core data, palynological and sedimentological changes in maritime Canada [*Mott et al.*, 1986; *Levesque et al.*, 1993; *Mayle et al.*, 1993], southern New England [*Peteet et al.*, 1990, 1993; *Maenza-Gmelch*, 1995], and southern Ontario [*Yu and Eicher*, 1995] attest to the colder climate that predominated, resulting in significant vegetational change and annual temperature depression estimates of 3°–4°C [*Peteet et al.*, 1993]. Glaciomarine diamictons dating to between 11,000 and 10,400 ^{14}C years B.P. are ascribed to a Younger Dryas advance in the Champlain Sea

Table 2. Results From Sensitivity Experiments

Model Run Designation	Description
Control	current climate [*Hansen et al.*, 1983]
11kAC	11k orbital parameters, land ice, and 18k SST for North Atlantic north of 25°N (see Rind et al., 1986 for more details)
11kAPC	11k orbital parameters, land ice, and SST in North Pacific 2°C colder than present north of the equator, 1°C colder than present south to 8°S, and elsewhere same as 11kAC.
11 kAPClimap	11k orbital parameters, land ice, and SST in North Pacific 2°C colder than *CLIMAP Project Members* [1981] north of the equator, and elsewhere same as 11kAC.

Results for the model runs represent averages of the last 5 years of 6-year simulations.

[*Lasalle and Shilts*, 1993], and marine stratigraphy from the Labrador Sea indicates that the Laurentide ice advanced through Hudson Strait and deposited detrital carbonate [*Andrews et al.*, 1994].

2.2. Previous Modeling of a Cold Younger Dryas North Atlantic

In an attempt to test the sensitivity of the climate to colder ocean temperatures similar to those of the Younger Dryas, in earlier experiments we cooled North Atlantic SST to glacial conditions [*Rind et al.*, 1986]. The downstream effect in Europe generally matched the strong evidence for an event that was thought then to be primarily restricted to the North Atlantic region [*Broecker et al.*, 1985; *Rind et al.*, 1986], and the model produced more snow downwind of the North Atlantic despite less oceanic evaporation, which also corresponds with the European paleoclimatic evidence of sudden and marked Younger Dryas glacial growth. The North Atlantic cooling also produced a small upwind effect in the model, but this was restricted to the east coast of North America. However, as the recent body of evidence has accumulated concerning a likely Younger Dryas North Pacific event, this model result does not explain the evidence of cooling in the North Pacific and land areas adjacent to it.

2.3. Evidence for Late Glacial North Pacific Regional Cooling

Keigwin's [1987] benthic isotope record from core RAMA 44 was the first isotopic evidence for the subarctic Pacific north of 50°N. (Figure 1, Table 1). The existence of a mid–Termination I break in planktonic foraminiferal ^{18}O in the western Pacific [*Kallel et al.*, 1988; *Keigwin et al.*, 1992] and changes in the eastern North Pacific [*Zahn et al.*, 1991; *McDonald and Pederson*, 1995] suggests that either a cooling or salinity/meltwater effect characterized the late glacial interval in the North Pacific. New cores from the northwestern Pacific reveal evidence

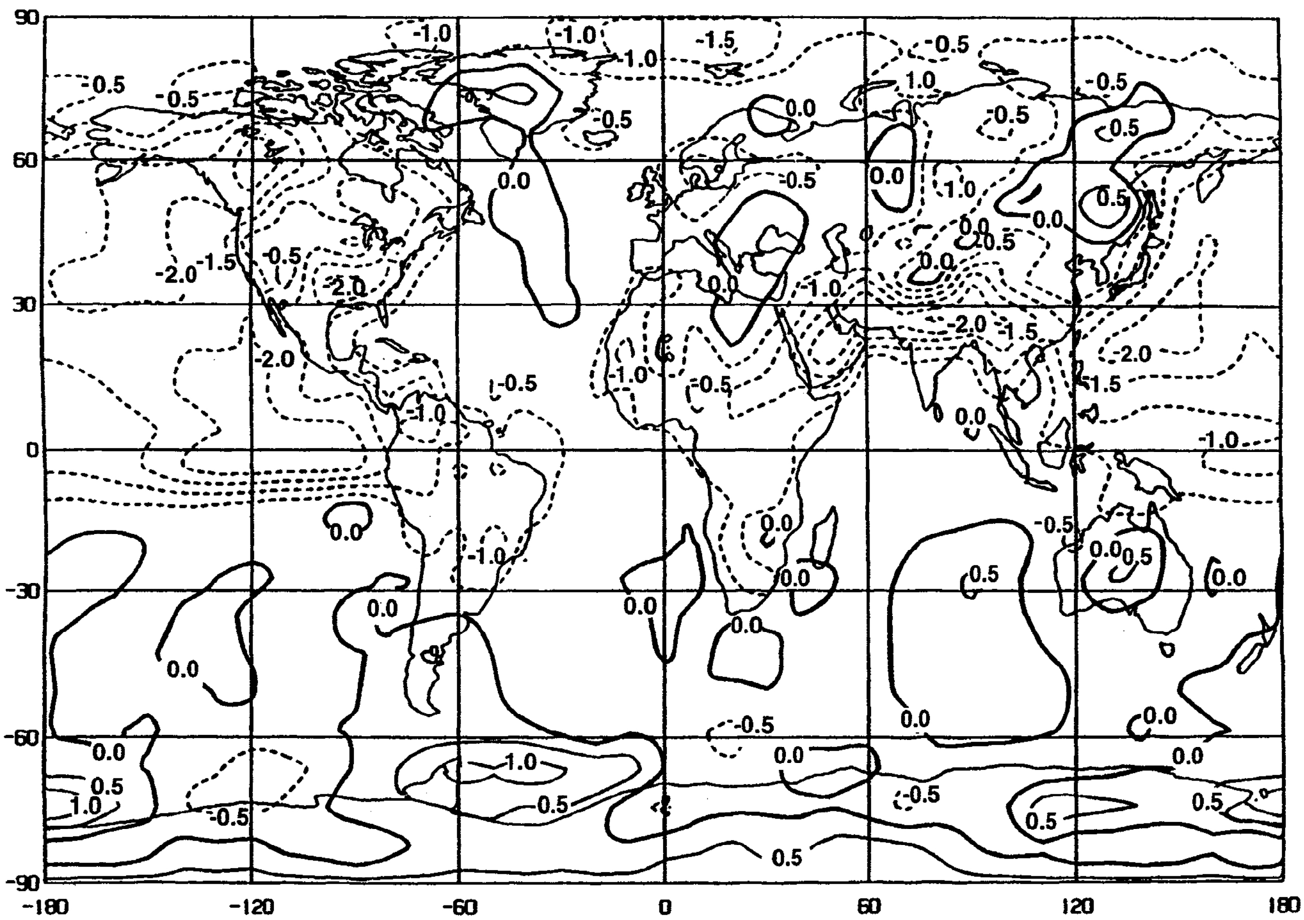

Figure 2. Change in annual surface air temperature due to colder North Pacific SSTs alone at 11 ka (11kAPC minus 11kAC), in degrees Celsius. The model's grid point standard deviation of temperature is about 0.5°C in most locations in an unforced 5-year run.

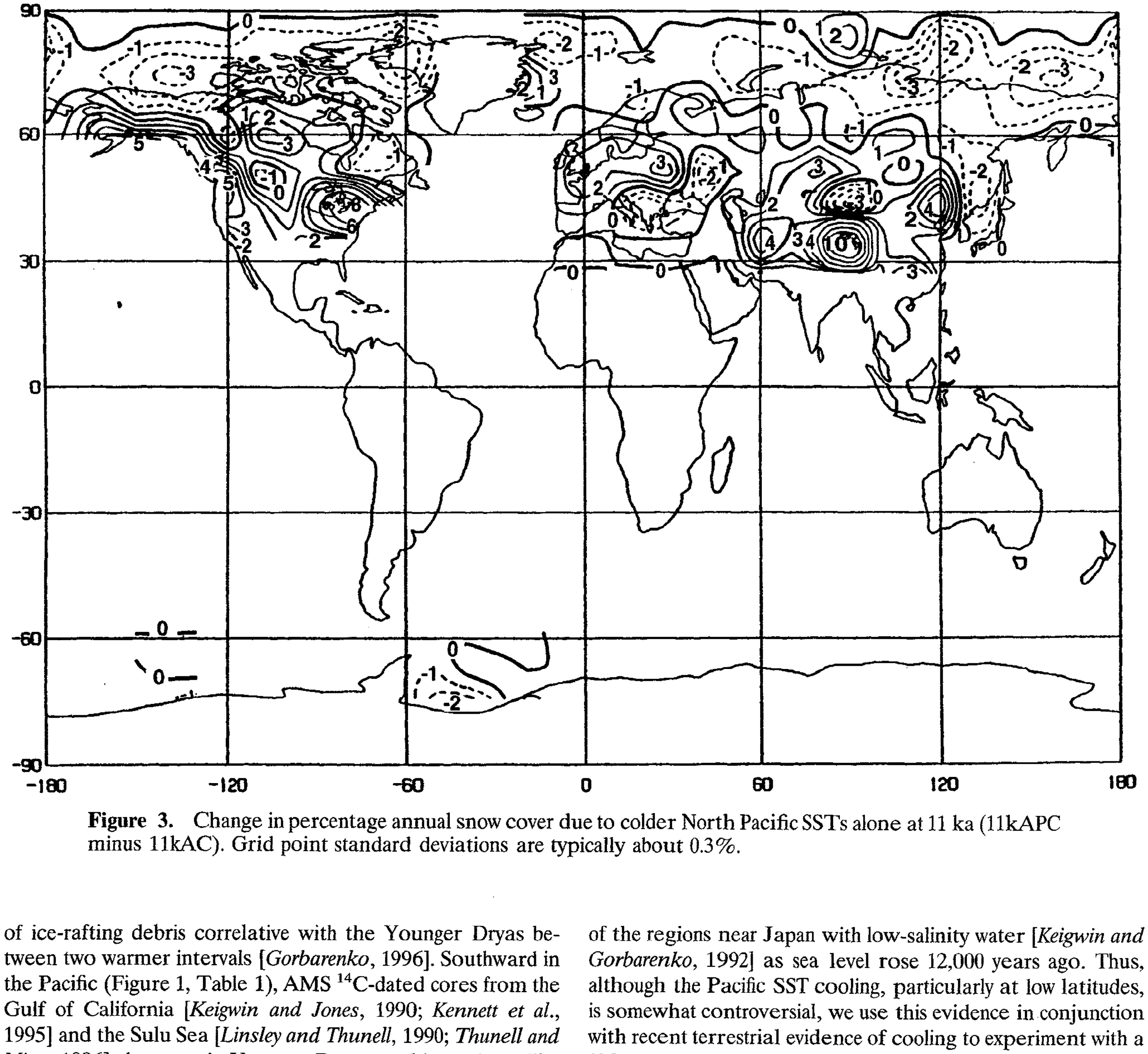

Figure 3. Change in percentage annual snow cover due to colder North Pacific SSTs alone at 11 ka (11kAPC minus 11kAC). Grid point standard deviations are typically about 0.3%.

of ice-rafting debris correlative with the Younger Dryas between two warmer intervals [*Gorbarenko*, 1996]. Southward in the Pacific (Figure 1, Table 1), AMS ^{14}C-dated cores from the Gulf of California [*Keigwin and Jones*, 1990; *Kennett et al.*, 1995] and the Sulu Sea [*Linsley and Thunell*, 1990; *Thunell and Miao*, 1996] also contain Younger Dryas aged isotopic oscillations that are attributed to North Pacific circulation changes [*Keigwin and Gorbarenko*, 1992; *Thunell and Miao*, 1996] and/or to widespread climatic variability [*Kennett and Ingram*, 1995; *Kotilainen and Shackleton*, 1995].

On land, scattered evidence also points to a reversal possibly correlative with the Younger Dryas (Figure 1, Table 1). In southwestern British Columbia and Washington, pollen records point to a cooling just prior to the Holocene warming [*Heusser*, 1973; *Hebda*, 1983; *Mathewes*, 1973, 1993]. Farther north, a southeastern Alaskan pollen record shows a similar pattern [*Engstrom et al.*, 1990; *Hansen and Engstrom*, 1996]. Finally, several coastal lake sections from Kodiak Island, Alaska [*Peteet and Mann*, 1994] show a clear reversal in lithology, pollen, and macrofossil stratigraphy dated by AMS ^{14}C between 11 and 10 ka, indicative of regional climatic cooling and/or drying.

Various Japanese sites also suggest a reversal which may be correlative with the Younger Dryas during this period [*Tsukada*, 1967; *Fuji*, 1982; *Igarashi et al.*, 1993]. Alternatively, others have claimed a unidirectional warming [*Heusser and Morley*, 1990] and attributed oceanographic changes to flushing of the regions near Japan with low-salinity water [*Keigwin and Gorbarenko*, 1992] as sea level rose 12,000 years ago. Thus, although the Pacific SST cooling, particularly at low latitudes, is somewhat controversial, we use this evidence in conjunction with recent terrestrial evidence of cooling to experiment with a 2°C North Pacific cooling in the GCM.

3. Model and Sensitivity Experiments

The general circulation model used for these experiments is GISS model II, described by *Hansen et al.* [1983]. The model solves the equations of mass, energy, momentum, and moisture, and it calculates radiative fluxes, surface fluxes, latent heating, and cloud cover. It has realistic topography on an 8° × 10° (latitude by longitude) horizontal resolution grid with fractional grid representation for land and ocean and nine atmospheric layers. Ground temperature calculations include the diurnal variation and seasonal heat storage, while ground hydrological parameters are a function of vegetation type. The control run is represented by a 5-year simulation of the modern climate, and results are shown by *Hansen et al.* [1983].

3.1. GISS GCM Sensitivity Experiments

We compare results from three sensitivity experiments (Table 2). The first (11kAC) prescribes glacial value North Atlantic SSTs down to 25°N with 11 ka boundary conditions. These conditions include 11 ka orbital parameters [*Berger*, 1978], land

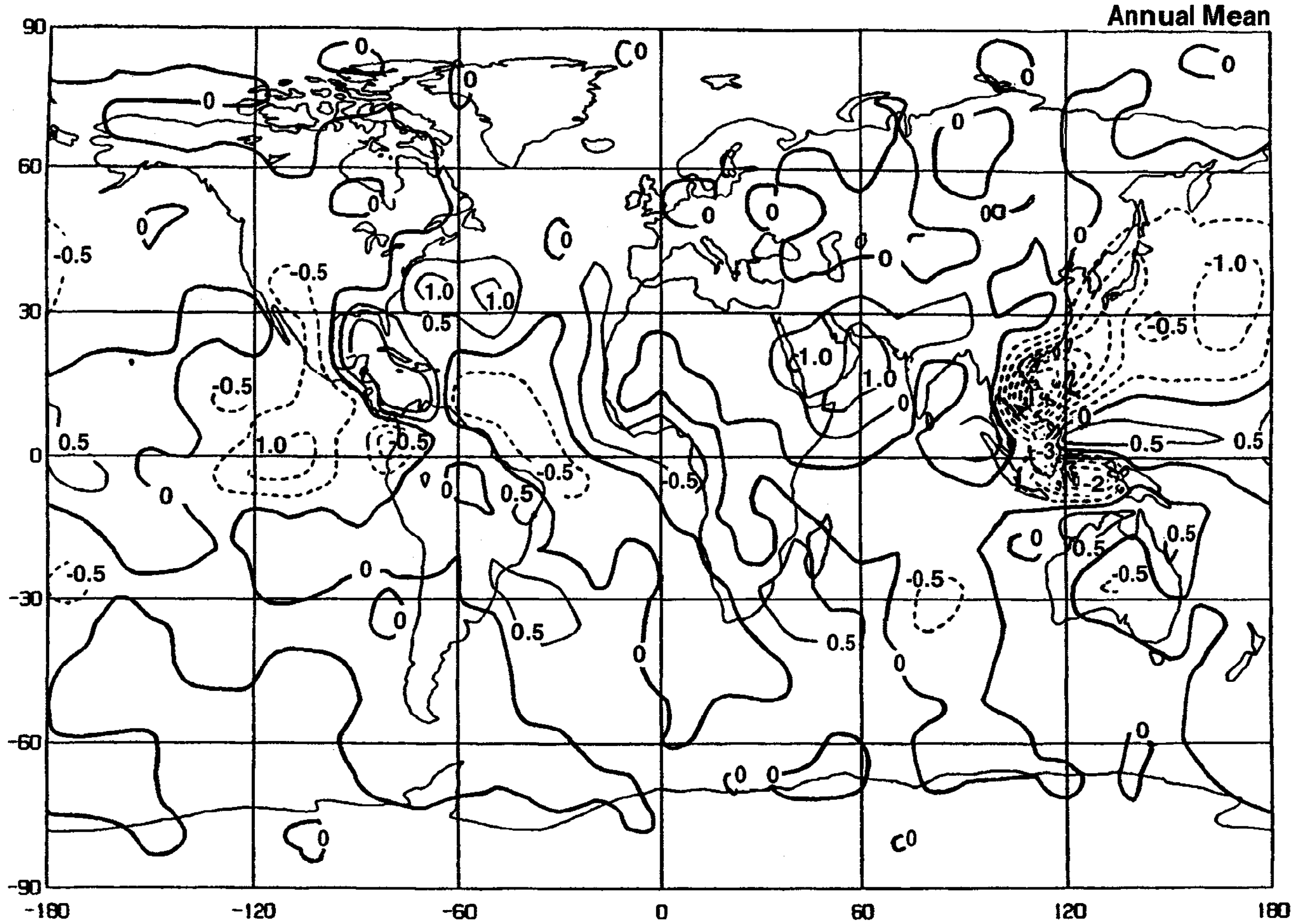

Figure 4. Change in annual evaporation (11kAPC minus 11kAC), in millimeters per day.

ice distribution [*Denton and Hughes*, 1981], along with sea level change approximately two thirds of the glacial decrease. These conditions were the same as those we used for a previous 2-year mean Younger Dryas simulation [*Rind et al.*, 1986], except that the results here represent a 5-year mean instead, which reduces the effects of natural interannual fluctuations of the model. The second experiment (11kAPC) is identical to the first but instead of modern North Pacific SSTs, we decrease North Pacific SST's by 2°C relative to the current climate. If we accept the latest Greenland ice core chronology with the timing of the Younger Dryas now as 13,000 to 11,600 years B.P. [*Taylor et al.*, 1993], the orbital values we used are too young by 600–2000 years. However, this difference is too small to affect the results of this experiment, except in slightly decreasing the high seasonality of 11,000 ka.

Our third sensitivity experiment (11kAPClimap) is the same as the second (11kAPC) except that we lower North Pacific *CLIMAP Project Members* [1981] (hereinafter referred to as *CLIMAP* [1981]) ice age values by 2°C, thereby testing the global sensitivity of the ice age to this cooling of the North Pacific.

3.2. North Pacific SST

We test the sensitivity of the GISS GCM to decreases in North Pacific SST using regional North Pacific evidence cited above for such cooling to direct our experiments. As the simplest experiment for testing the sensitivity of the model to North Pacific temperature depression, we changed the SST's north of the equator by -2°C relative to current values and by -1°C relative to current values south to 8°S. We chose this large region because of the paleoceanic evidence of change ranging spatially from cores in the western Pacific [*Keigwin et al.*, 1992; *Kotilainen and Shackleton*, 1995] to those in the eastern Pacific [*Zahn et al.*, 1991], and as far south as the equator [*Boltovskoy*, 1990; *Linsley and Thunell*, 1990] (Table 1, Figure 1), though fewer sites and recent controversy [*Thunell and Miao*, 1996] make the lower latitudes less certain. Additionally, as was noted above, evidence on land exists for a possible Younger Dryas correlation from Japan to the western coast of North America. As one moves south latitudinally, this points to the problem of disparity in land and *CLIMAP* [1981] ocean temperature reconstructions for the last glacial maximum (LGM) that remains a serious and perplexing problem. Because *CLIMAP* [1981] may have seriously underestimated the drop in SST [*Rind and Peteet*, 1985; *Beck et al.*, 1992; *Stute et al.*, 1992; *Emiliani and Ericson*, 1991; *Guilderson et al.*, 1994] this study has implications for the climate of the LGM as well as the late glacial.

4. Results

The primary result of the experiments is that colder North Pacific SSTs have a major effect on northern hemisphere surface air temperature (Figure 2). In contrast to the 11kAC run in which only North Atlantic SSTs were cooled and a downstream effect over land was noted, here the cooling extends

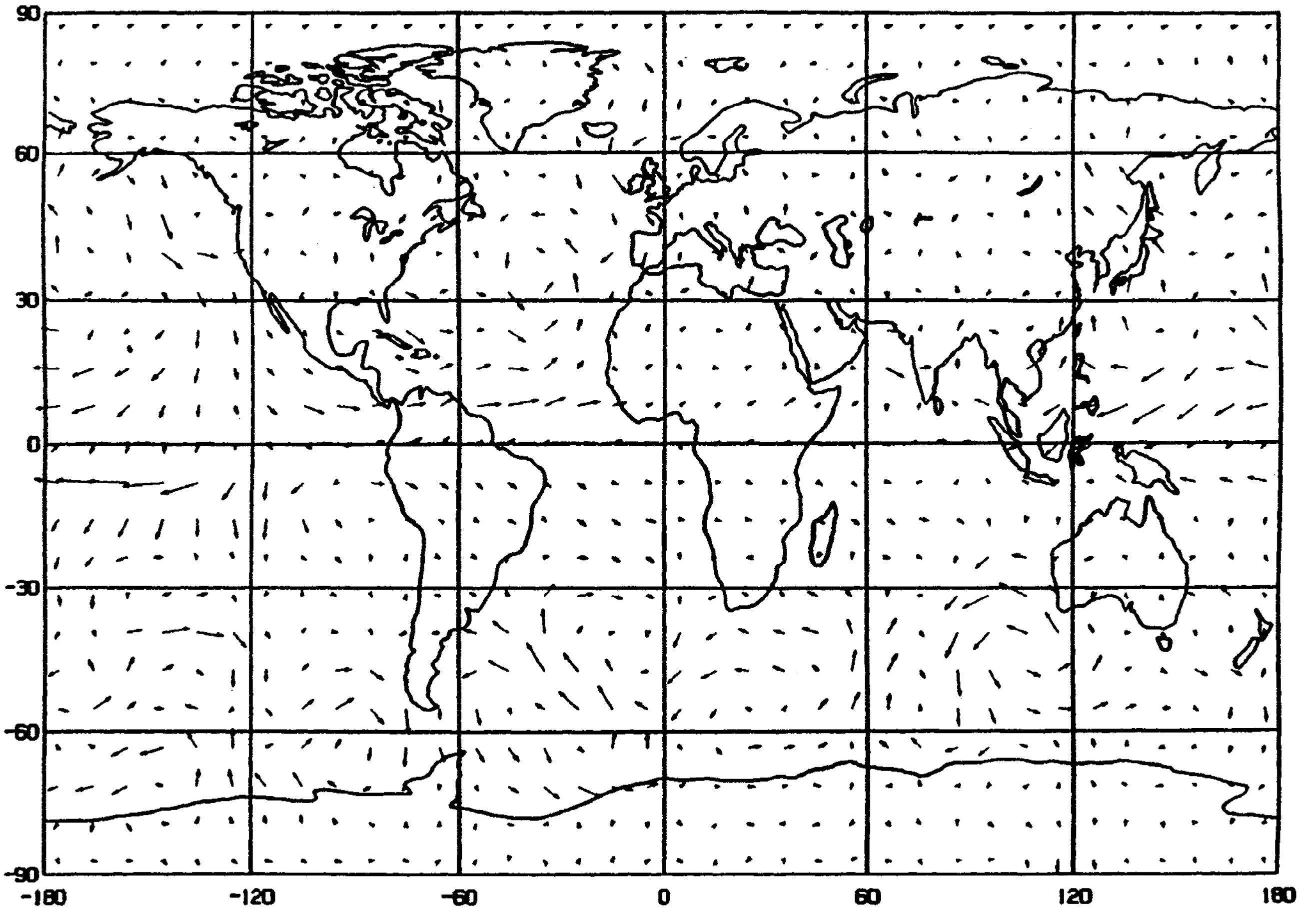

Figure 5. Change in annual surface air winds (11kAPC minus 11kAC). The strength of the wind change is noted by the length of the arrow.

throughout the northern hemisphere, including an enhancement of cooling downwind of the Atlantic relative to that produced by cooling only North Atlantic SSTs. The primary North American cooling signal is 1.5°–2.5°C in most locations; this is 3–5 times the GCM's grid point standard deviation (σ) of temperature and coherent over the entire continent. The Eurasian cooling is only marginally significant locally but is highly significant averaged over the continent. The factors contributing to this large Pacific SST-generated cooling and increase in snow cover (Figure 3) are identified as we discuss the following characteristics of the 11kAPC climate.

4.1. Planetary Radiation Balance

One way to understand the hemispheric impact of a regional change in SST is by examining the resulting perturbations of the planetary radiation budget. The SST reduction itself, communicated to the atmosphere above, would induce a negative feedback; i.e., the cooler atmosphere would radiate less to space, which would act to restore the original SST if it were allowed to respond. This is more than offset, however, by a variety of positive feedbacks in the cooler SST simulation, including increases in reflective low level (+0.4%, 3.5σ) and middle level (+0.3%, 3σ) cloud cover, decreasing column amounts of water vapor (−1.0 mm, 17σ), and increasing snow cover (+0.5%, 10σ) and depth (+0.3 mm, 4σ). The net result of all feedbacks is that the shortwave radiation absorbed and longwave radiation emitted by the planet each decrease by about 1 W/m^2 (3σ and 11σ changes, respectively) while the net radiation at the top of the atmosphere (absorbed solar minus outgoing longwave) remains virtually the same.

4.2. Propagation of Signal Around the Globe

This global picture does not explain the meteorological processes that cause the signal in the North Pacific to propagate around the globe. Water vapor, and particularly evaporation from the ocean surface, is the key element of the interaction. The difference in evaporation between the runs with and without the North Pacific cooling is shown in Figure 4. The complex pattern of changes occurs both because the evaporation response to a spatially uniform SST change is larger in warm parts of the Pacific than in cooler parts and because evaporation depends on atmospheric humidity (specifically the sea-air humidity contrast) and on surface wind speed.

It is most convenient to start in the west Pacific and trace the signal eastward in the direction of the prevailing westerly winds in midlatitudes. In the west Pacific, the warmest part of the Pacific basin, evaporation decreases by the largest amount (5σ) because of the nonlinear temperature dependence of saturation humidity. Thus drier air blows eastward across the Pacific. Over the central Pacific, evaporation actually increases slightly (3σ) at low latitudes despite the lower SST (Figure 4). This is the result of two factors: (1) the drier air advected from the west increases the air-sea humidity contrast, and (2) the overall Pacific cooling induces anomalous high pressure and anticyclonic flow in the overlying atmosphere, which strengthens the low-latitude trade winds at the surface over the central Pacific

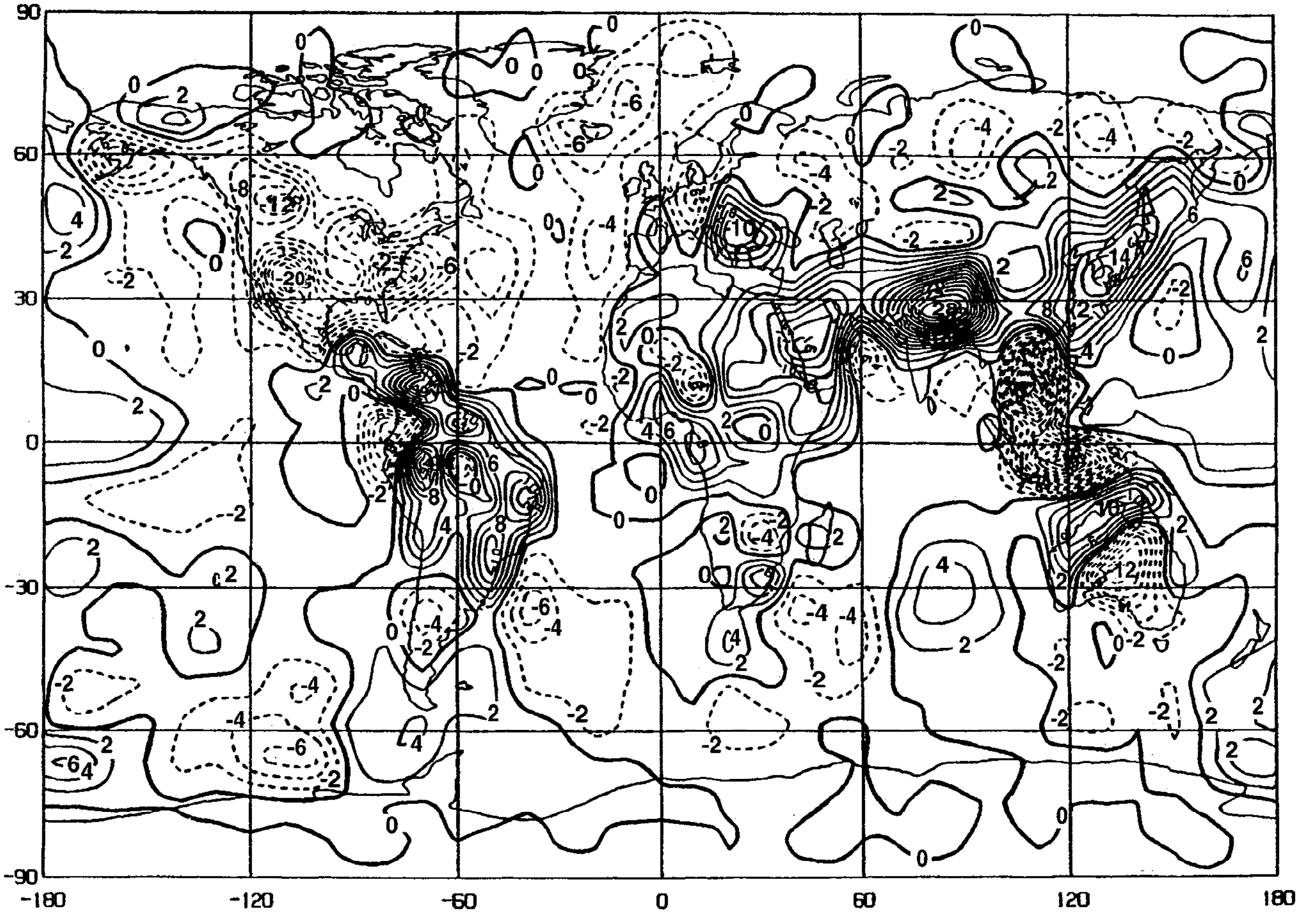

Figure 6. Change in annual sensible heat flux (11kAPC minus 11kAC), in watts per square meter. Upward fluxes are negative by convention, so a negative change denotes a stronger upward heat flux, cooling the surface.

(Figure 5). In the east Pacific the effect of reduced SST mostly dominates again (but less than in the west owing to the cooler east Pacific SST), and evaporation slightly decreases both over this region (2–3σ) and over most of North America (3–5σ), which has also cooled.

Averaged over the entire northern hemisphere ocean, evaporation decreases (-0.07 mm/d, 3.5σ), producing a somewhat larger decrease in precipitation (-0.17 mm/d, 3σ). Thus there is less latent heat release, which cools the atmosphere. The cooler, drier air blows over North America, leading to increased (3–5σ) sensible heat fluxes there (Figure 6) which lower temperatures over land as well (Figure 2). The cooler North American land surface evaporates less moisture (Figure 4) and receives less precipitation (Figure 7). The drier air reduces cloudiness over most of North America, so absorption of sunlight increases, but this is more than offset by the cooling effect of the increased sensible heat fluxes.

Along the east coast of North America, the cooling decreases because of the maritime influence of the Atlantic. However, in the eastern US the cooling is still comparable to that which results from the upwind influence of North Atlantic cooling alone [see *Rind et al.*, 1986, Figure 12c]. Since the Atlantic is at the same temperature in runs 11kAPC and 11kAC, the dry air flowing over the Gulf Stream from North America causes a slightly increased (2–3σ) evaporation there, a modest but marginally significant increase in precipitation, and a low-pressure anomaly that brings a cool northeasterly flow over the east coast in winter.

East of the Gulf Stream, sensible heat flux and evaporation changes are either not statistically significant ($<2\sigma$) or weaker; yet marginally significant surface cooling over Eurasia nonetheless occurs, mostly equatorward of 45°. This effect appears to be associated with an increase in cloud cover and reduction of sunlight absorption over most of Eurasia (Figure 8). The different anomalies in cloudiness over North America and Eurasia must be interpreted with caution owing to the primitive nature of the cloud parameterization in this version of the GCM. Plausibly, though, the difference reflects the fact that air flowing across North America in 11kAPC has been subjected to both cooling and weaker evaporation, with the latter dominating the change in relative humidity. By contrast, the air flowing over Eurasia has experienced no evaporation anomaly (since 11kAC and 11kAPC have the same Atlantic SSTs), so that cooler air increases relative humidity and thus cloud cover.

Because the North Pacific cooling was prescribed to occur over the entire northern Pacific, the SST gradient across the equator is much sharper and more hemispherically asymmetric in 11kAPC. Thus the Hadley cell artificially strengthens, and its rising branch shifts southward, causing large positive and negative precipitation anomalies just south and north of the equator, respectively, especially east of the date line and in the Asian monsoon region (Figure 7). The imposed tropical SST

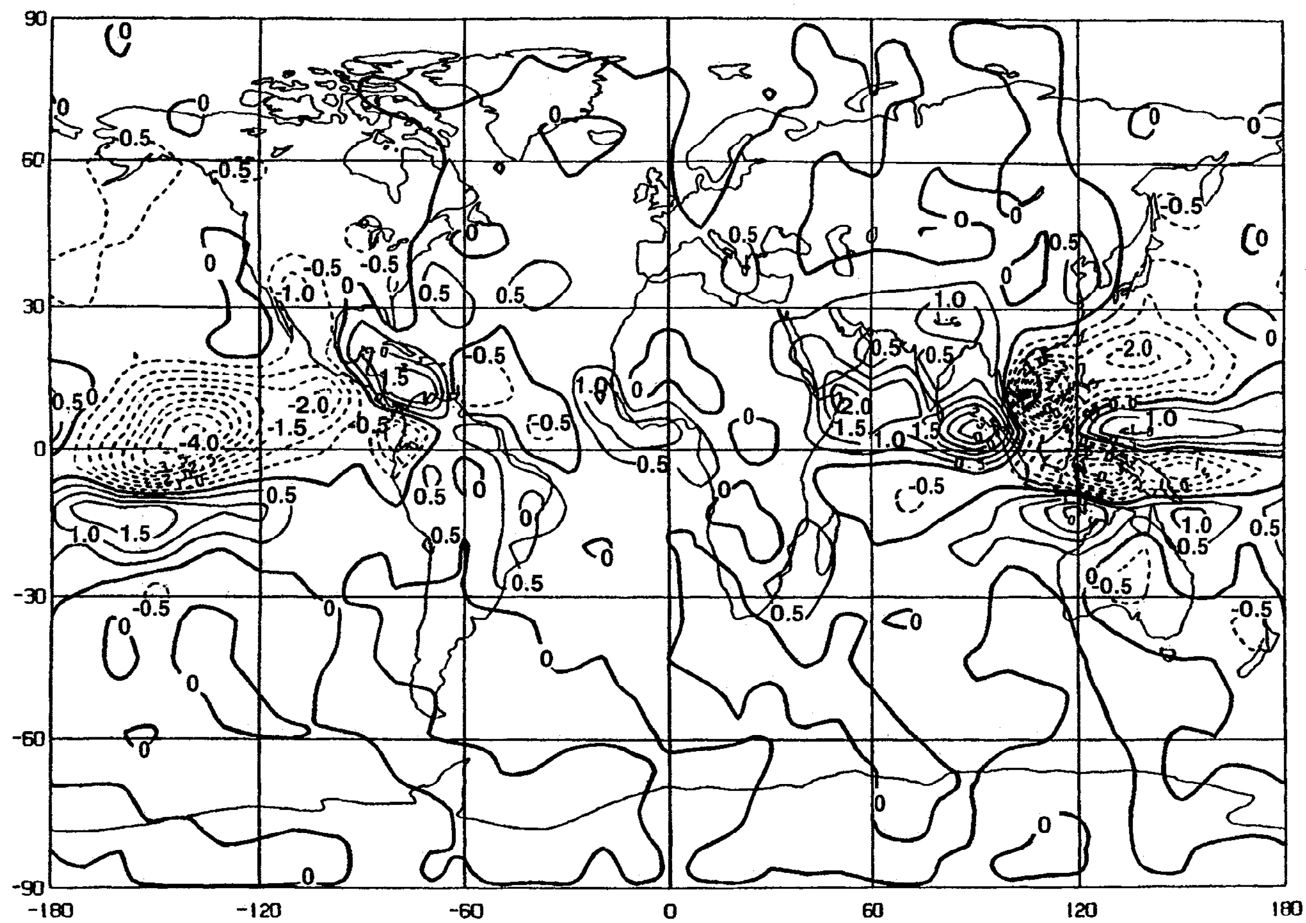

Figure 7. Change in annual precipitation due to colder North Pacific SSTs (11kAPC minus 11kAC), in millimeters per day.

changes might be expected to induce midlatitude teleconnection-type anomalies. However, remote influences on North American circulation are insignificant (see Figure 5) in the GCM. In present-day precipitation climatologies over land, El Niño–Southern Oscillation signals are in fact not a significant continental-scale mode of variation over middle and high latitudes [*Dai et al.*, 1997], although regional effects can be detected. The effect of the tropical SST changes on meridional fluxes of latent and sensible heat is overwhelmed in midlatitudes by the local and downstream effects of decreasing evaporation on atmospheric humidity in the midlatitude Pacific. In fact, the return branch of the Hadley cell, which is a sink of subtropical moisture and a source for the Intertropical Convergence Zone, weakens in the subtropics, the opposite of what is needed to explain a midlatitude water vapor decrease. Thus the results over the northern continents are not likely to be sensitive to the particular pattern of SST change chosen for the experiment. In particular, midlatitude changes are in themselves significant enough to cause large changes over continents.

4.3. Alternate Cooling of North Pacific [*CLIMAP*, 1981] by 2°C

Our results from the experiment described above are similar to a parallel experiment in which we changed the SSTs north of the equator to *CLIMAP* [1981] values minus 2°C. (These original CLIMAP values were similar or warmer than today's in much of the region, even extending as far north as 45°N [see *Rind and Peteet*, 1985]). This North Pacific (CLIMAP −2°C) SST change resulted in reflective low level (+1.3%) and middle level (+0.3%) cloud cover increases, decreased column amounts of water vapor (−1.0 mm), increased snow cover (+0.3%), and depth (0.1 mm). The net result of these changes is that the net radiation at the top of the atmosphere decreases by 1.4 W m^{-2} (4σ). Thus if the SST were allowed to change, it would cool even further than was originally proposed. Because of the spatially varying CLIMAP SST changes relative to the present, the patterns of evaporation, surface wind, etc. changes differ somewhat from those in the previous experiment. The basic result of weakened Pacific evaporation and humidity and cooler air leading to downwind cooling over North America remains the same, however.

5. Discussion

In contrast to our previous sensitivity experiments concerning a colder North Atlantic, this North Pacific SST change produces an entire northern hemispheric response. The large sensitivity of the GCM to a SST change, the magnitude of which may not be unreasonable for the Younger Dryas or the LGM climate, suggests that the North Pacific Ocean participation in rapid climate change might be important. Thus additional high-resolution Pacific information is needed to determine the causes of late glacial fluctuations in stable isotopes,

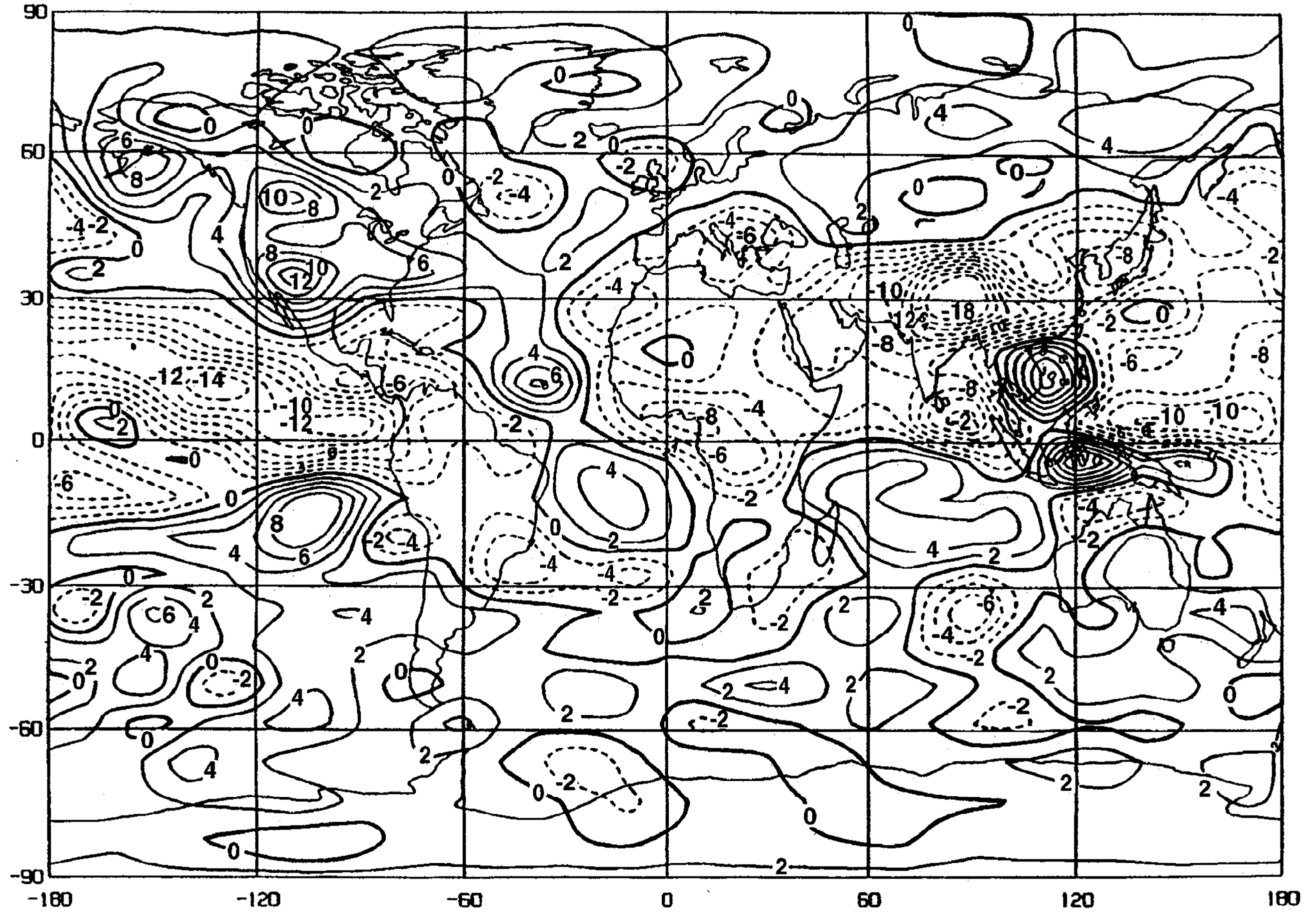

Figure 8. Change in annual absorption of sunlight at the surface (11kAPC minus 11kAC), in watts per square meter.

foraminiferal and diatom species, opal, and organic carbon, and specifically how and what kinds of changes in ocean circulation may have taken place.

The importance of the North Pacific in climate change may have been previously neglected. The geographic extent (80° of longitude) is almost twice that of the Atlantic at 50°N, thus a vast and extensive surface area. A very large carbon reservoir, it is thus capable of producing major changes in global carbon fluxes. A fundamental question concerning the formation of the Laurentide ice sheet is the source of moisture, specifically whether moisture could have arrived from the North Pacific as well as the North Atlantic. *Ruddiman et al.* [1980] assumed that the Laurentide ice sheet originated from a warmer North Atlantic on the basis of the isotopic signal, which they interpreted to indicate ice expansion while planktonic SSTs were warm. *Miller and de Vernal* [1992] used this argument to support the concept of future greenhouse warming leading to ice sheet growth. However, the paleoisotopic interpretation of ice sheet growth is suspect because of complexity in interpreting the deep ocean isotopic signal, in part because the isotopic change is partially due to deep ocean temperature [*Chappell and Shackleton*, 1986]. Large and rapid fluctuations in Greenland temperatures around this time suggest that ice buildup may not have occurred until about 70 ka. We also question the North Atlantic as the sole source for this accumulation. According to *Peixoto and Oort* [1983], precipitation minus evaporation ($P - E$) is positive throughout the year today in the region that was covered by the Laurentide ice sheet. Tracer modeling of precipitation sources in the GISS GCM [*Koster et al.*, 1986] indicates that the North Pacific is a major source for northern Canada in fall and winter, which are the significant seasons for major snow accumulation. However, the scale of model resolution and the relatively primitive parameterizations of surface fluxes and moist convection used in model II may limit the accuracy of the results.

In the GISS GCM, model results consistently produce increased snow cover in temperate latitudes immediately downwind of colder Northern hemisphere oceans, even when evaporation is less, because the lower temperatures cause more of the precipitation to fall as snow. For example, the effect of colder North Pacific SST by itself is to produce an increase in annual northern hemisphere land snow cover of 0.8% (3σ). The Younger Dryas marine-terrestrial paleoclimatic data suggest that this relationship is a valid one because of the overwhelming evidence for colder North Atlantic temperatures and correlative glacial advances surrounding the North Atlantic. Thus if the North Pacific Ocean were colder than the *CLIMAP* [1981] reconstruction, this experiment implies that it would have cooled the northern hemisphere and that source regions for the Laurentide Ice Sheet would have been affected (Figure 3). Higher-resolution terrestrial and marine sampling throughout the last 30,000 years is needed to explore this relationship further. Although ocean variability questions usually focus upon the North Atlantic, idealized ocean models have been shown to produce multiple equilibria, including solutions in which the roles of the North Atlantic and North Pacific are reversed [*Marotzke and Willebrand*, 1991].

Sources of late glacial Pacific marine-atmospheric variability revolve around the relationship of the North Pacific and Arctic Oceans. Today, the Gulf of Alaska is one of the most active meteorological regions on Earth. Climate of the region affects the oceanography by means of both wind-induced currents and coastal currents driven by differences in water density from the large runoff of fresh water along the coast of southeast Alaska [*Wilson and Overland*, 1986]. During the late glacial, with higher seasonality and most of the coastal region from Kodiak Island to British Columbia covered with extensive ice [*Hamilton and Thorson*, 1983], during summer the freshwater runoff would have been far greater than today, increasing the density gradient that enhances the density-driven component of the gulf-wide coastal current [*Royer*, 1982]. Extensive floating ice or shelf-based ice caps that developed seaward of the Alaska Peninsula [*Hamilton and Thorson*, 1983; *Mann and Peteet*, 1994] would have added to the rapidity of albedo and meltwater feedbacks, which in turn could induce deep water formation, by analogy with Antarctic ice shelf processes [*Foldvik et al.*, 1985].

As sea level was rising as a result of global ice retreat, the connection of the Arctic with the North Pacific would have greatly changed the atmosphere-ocean dynamics, and in particular the high-pressure systems characteristic of winter conditions over ice-covered regions of the Arctic. Recent model experiments [*Shaffer and Bendtsen*, 1994] suggest that connection of the North Atlantic with the North Pacific due to the Bering Strait would have favored a shutdown of North Atlantic Deep Water due to the influx of cool, relatively fresh North Pacific water. However, the timing of the connection appears to be about 10,500 years B.P., based upon AMS-dated macrofossils from the Bering land bridge [*Elias et al.*, 1996]. This Pacific-Atlantic connection perhaps contributes therefore to the sudden warming at 10 ka which is a dominant signal in terrestrial pollen records throughout high latitudes of the northern hemisphere. A large influx of fresh water (8.6 km^3/h) from the drainage of Lake Agassiz to the Arctic at the close of the last glaciation 9900 years B.P. [*Smith and Fisher*, 1993] may also have had a role in the rapid and abrupt Holocene warming and change in atmospheric circulation patterns.

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